

The Formation of Massive Stars through stellar collisions

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Abstract. In this review, I present the case for how massive stars may form through stellar collisions. This mechanism requires very high stellar densities, up to 4 orders of magnitude higher than are observed in the cores of dense young clusters. In this model, the required stellar densities arise due to gas accretion onto stars in the cluster core, including the precursors of the massive stars. This forces the core to contract until the stellar densities are sufficiently high for collisions to occur. Gas accretion is also likely to play a major role in determining the distribution of stellar masses in the cluster as well as the observed mass segregation. One of the main advantages of this mechanism is that it explicitly relies on the cluster environment in order to produce the massive stars. It is thus in a position to explain the relation between clustered and massive star formation which is not an obvious outcome of an isolated accretion mechanism. A recent numerical simulation supports this model as the cluster core increases its density by 10^5 during gas accretion. Approximately 15 stellar collisions occur (with $R_{coll} = 1$ au) in the cluster core, making a significant contribution to the mass of the most massive star.

1. Introduction

The formation of massive stars, due to their large chemical and energetic feedback, is an important issue not just for the field of star formation but also for many other areas of astronomy from the interstellar medium to galaxy formation. The difficulties in forming massive stars are two-fold. One, how does that much mass get accumulated by one star, and two, can the accumulation of this matter overcome the large radiation pressure from the star. The formation of low-mass stars appears trivial in comparison as the stellar masses are not vastly different from estimates of the Jeans mass in molecular clouds and as the stellar luminosities are not sufficiently large to affect the accretion process. Massive stars, in contrast, have masses up to 100 times the estimated Jeans mass in molecular clouds. This implies that the majority of their mass is probably due to subsequent accumulation rather than the initial collapse (see A. Maeder, this volume). Of potentially more of an impediment is the radiation pressure from stars more massive than $\approx 10 M_{\odot}$ which can act on the infalling dust grains to reverse the infall and halt the accretion process (Yorke & Krugel 1977; Yorke 1993; Beech & Mitalas 1994). There are possible solutions to this impediment involving changing the properties of the dust grains (Wolfire & Cassinelli 1987) or perhaps a

non-isotropic radiation flux such that matter can more easily accrete onto the star's equator from an accretion disc (c.f. H. Yorke, this volume). In this paper, I consider an alternative model whereby the accumulation of mass comes from stellar collisions. The accumulation of such optically-thick, dust-free entities as stars eliminates any problem due to radiation pressure.

In constructing a theory for massive star formation, we should make use of all the available observational clues. One such clue is that massive stars are not generally found in isolation but appear to form in the central regions of rich young stellar clusters (Zinnecker, McCaughrean & Wilking 1993; Hillenbrand 1997; Clarke, Bonnell & Hillenbrand 2000; Mermilliod 2001). Even runaway OB stars are probably most easily explained as having been ejected from such a stellar cluster (Clarke & Pringle 1992). Testi et.al. (1997) have argued that there is a strong correlation between the mass of the most massive star in a cluster and the cluster's mean stellar density. Although this data is still compatible with random pairing from an IMF (Bonnell & Clarke 1999), such a correlation would imply a potential causal relationship between cluster density and the mass of the most massive star.

In considering the clustered environment for massive star formation, there are a number of observations that need to be considered. In addition to the large number of accompanying low-mass stars, the relatively large stellar densities and that the mass spectrum is similar to a field star IMF, one feature that needs to be explained is the observed mass segregation (Hillenbrand 1997; Carpenter et.al. 1997; Hillenbrand & Hartmann 1998). For example, the Orion Nebula cluster (ONC) shows a segregation of massive stars towards the centre of the cluster. This appears to be the case not only for the most massive O stars but also for the intermediate-mass stars present in the cluster.

Lastly, but perhaps most importantly, the fact that massive stars form in stellar clusters implies that we need to consider a dynamical formation scenario. The dynamical time of the cluster as a whole is comparable to the formation time of the individual stars. That implies that the stars move around in the cluster while they are forming. We have to thus abandon a static formation scenario where the environment can be ignored. Although this causes significant complications, it can also provide simple physical processes that combine to determine the resultant stellar properties.

2. Fragment masses

The most straight forward solution for massive star formation would be that a massive clump of $\approx 50 M_{\odot}$ collapses to form the star. This scenario is complicated by the dense cluster environment. As the massive stars are located in the cluster core, the pre-stellar clump would have to fit in between the neighbouring stars, which, in the core of the ONC are separated by ≈ 5000 au. In order for the clump to be gravitationally bound, it must have a Jeans length smaller than this separation:

$$R_J = \left(\frac{5R_g T}{2G\mu} \right)^{1/2} \left(\frac{4}{3}\pi\rho \right)^{-1/2} \lesssim 5000 A.U., \quad (1)$$

where ρ is the gas density and T the temperature, R_g is the gas constant, G is the gravitational constant, and μ is the mean molecular weight. This implies that for typical temperatures in molecular clouds, the gas density must be very high. This also makes sense as one would expect the highest gas densities in the deepest part of the potential well (Zinnecker et.al. 1993).

The mass of the resultant star can then be estimated from the Jeans mass, the minimum mass to be gravitationally bound:

$$M_J = \left(\frac{5R_g T}{2G\mu} \right)^{3/2} \left(\frac{4}{3}\pi\rho \right)^{-1/2}. \quad (2)$$

In the core of the ONC, the Jeans mass is then of order $0.3M_\odot$, much smaller than the most massive star of $50M_\odot$, or the mean stellar mass of $5M_\odot$ (Zinnecker et.al. 1993; Bonnell, Bate & Zinnecker 1998). Something else is needed in order to explain the observed masses. Furthermore, from the above equations it is obvious that the fragment mass should be smallest in the centre of clusters as the gas density is likely to be largest there. The initial masses from fragmentation in a stellar cluster should therefore result in an inverse mass segregation, with small stellar masses in the core (Bonnell, Bate & Zinnecker 1998).

Investigations of the dynamics of young stellar clusters have shown that dynamical mass segregation, the sinking of massive stars due to two-body relaxation, cannot explain the location of the massive stars (Bonnell & Davies 1998). Clusters such as the ONC are too young for the massive stars that form the Trapezium to have sunk from a significant distance from the cluster core. We are thus left with a formation process that occurs in situ but that does not reflect the initial fragment or Jeans mass.

3. Stellar collisions

If stellar collisions are responsible for the formation of massive stars (eg. Bonnell, Bate & Zinnecker 1998), then the timescale for multiple collisions has to be less than the observed age of the massive stars. Although it is difficult to ascertain the exact ages of massive stars, we know that in Orion, the massive stars are younger than a few million years and potentially as young as a few $\times 10^5$ years. The collisional timescale t_{coll} is related to the stellar properties as (Binney & Tremaine 1987)

$$\frac{1}{t_{coll}} = 16\sqrt{\pi}v_{\text{disp}}R_*^2 \left(1 + \frac{GM_*}{2v_{\text{disp}}^2 R_*} \right), \quad (3)$$

where n is the density of stars in the cluster, v_{disp} is the velocity dispersion, and M_* , R_* are the mass and radius of the star undergoing the collision. Figure 1 plots the collisional timescale as a function of stellar density for collisions involving a $10 M_\odot$ star assuming a $10 R_\odot$ collisional radius. The velocity dispersion is assumed to be 2 km/s. We can see from Figure 1 that for densities typical of young stellar clusters ($n \approx 10^3$ stars pc^{-3}), the collisional timescale is $> 10^{10}$ years. In order to get a collisional timescale of order $\lesssim 10^5$ years, a stellar density of $\gtrsim 10^8$ stars pc^{-3} is required.

Young stellar clusters are relatively dense agglomerations of stars. The Orion Nebula Cluster (ONC), for example, has a mean stellar density of $n \approx 10^3$

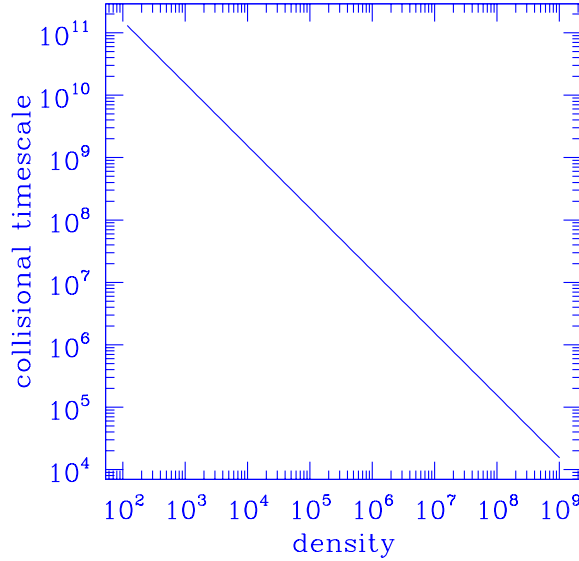


Figure 1. The collisional timescale (in years) is plotted as a function of the density in a stellar cluster in stars pc^{-3} . A velocity dispersion of 2 km/s, a stellar mass of $10 M_{\odot}$, and a collisional radius of $10 R_{\odot}$ are assumed.

stars pc^{-3} (Hillenbrand 1997). The core of the ONC is considerably more dense with $n \approx 2 \times 10^4$ stars pc^{-3} (McCaughrean & Stauffer 1994). From Figure 1 we see that the corresponding collisional timescale is $\approx 7 \times 10^8$ years. Clearly collisions cannot play an important role in the present conditions of the ONC. If stellar mergers are an important process in massive star formation, then the required stellar density of $n \gtrsim 10^8$ stars pc^{-3} implies that the ONC would have had to undergo a high density phase. The main question is then what process could have lead to such a short-lived but high-density phase. In the following sections we consider how accretion in stellar clusters may lead to such a scenario.

4. Accretion and the IMF

Observations of young stellar clusters reveal that they generally contain significant amounts of mass in the form of gas. This gas can amount up to 90 % of the total cluster mass (Lada 1991). Accretion of this gas can thus be an important factor in determining the masses of individual stars as well as the properties of the stellar cluster.

Numerical simulations of accretion in clusters have found that accretion naturally results in a mass segregated cluster (Bonnell et.al. 1997, 2001a). This occurs as the cluster potential funnels the gas down to the centre of the cluster where it is accreted by whatever stars happen to be there. The non-uniform accretion rates then result in the most massive stars being located in the centre

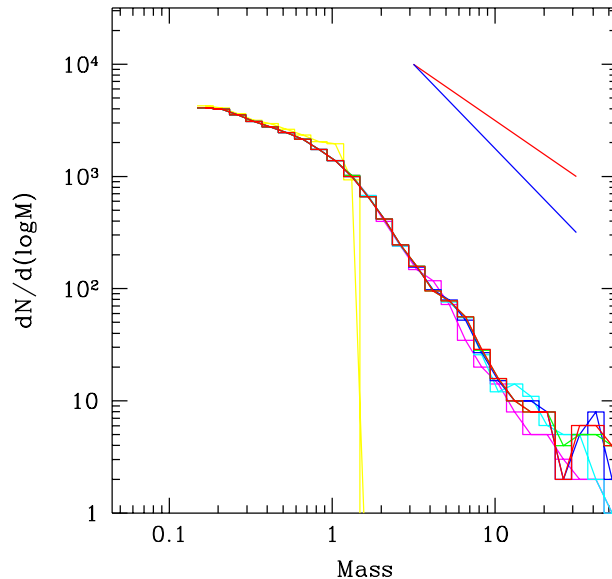


Figure 2. The Initial mass function is plotted that results from an accreting cluster. The accretion is assumed to be tidal accretion when the gas dominates the cluster potential followed by Bondi-Hoyle accretion when the stars dominate the potential in the cluster core. The accretion results in a $\gamma = -1.5$ IMF for low-mass stars and a steeper $\gamma \approx -2.5$ for high-mass stars (Bonnell et.al. 2001b).

of the cluster. In general, the resulting cluster demonstrates a degree of mass segregation comparable to that found in young stellar clusters.

Another finding of these numerical simulations is that there are two different physical regimes for the accretion, depending on whether the gas or the stars dominate the gravitational potential (Bonnell et.al. 2001a). When the gas dominates the potential, the motions of the stars and the gas are determined by the changing gravitational potential as the gas collapses. In this regime, the stellar and gas motions are similar and the accretion rate is determined by each star's tidal radius relative to the cluster potential. Material that moves inside the tidal radius gets accreted by the star. This assumes that the gas is initially unsupported, as is expected if it is able to fragment to form the large number of stars in the cluster.

The second regime occurs when the stars dominate the gravitational potential. In this case, the stars virialise and have motions uncorrelated to those of the gas. The gas velocity relative to a star is therefore large such that it is the determining factor as to whether the gas is bound to the star. The accretion rate in this case is the common Bondi-Hoyle accretion which depends on the local gas velocity and the star's mass, but not on the external potential.

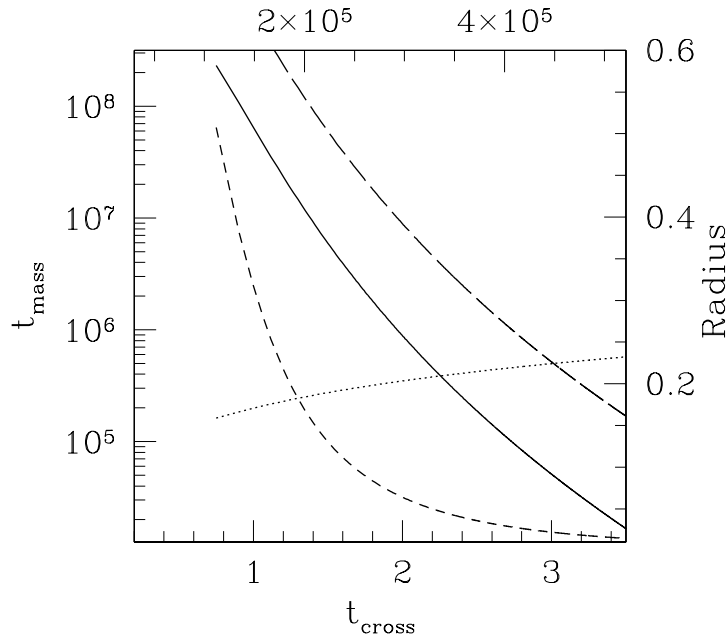


Figure 3. The evolution of an accreting cluster is shown where the cluster shrinkage is modelled by equation (6). The accretion timescale (dotted line) increases while the collisional timescales (solid and long-dashed lines) decrease reflecting the change in cluster radius (short-dashed line). The collisional radii are taken to be 0.1 and 0.01 au. (from Bonnell et.al. 1998)

Using these two different regimes for the gas accretion, Bonnell et.al. (2001b) showed how accretion in stellar clusters can result in a double power-law IMF where the low-mass stars have a shallow $\gamma \approx -1.5$ (where Salpeter is $\gamma = -2.35$) power-law due to the tidal lobe accretion while the high-mass stars have a steeper power-law ($\gamma \approx -2.5$) due to the subsequent Bondi-Hoyle accretion. The high-mass stars accrete the majority of their mass in the stellar dominated regime as they form in the core of the cluster where the stars (due to their high accretion rates) first come to dominate the potential.

5. Accretion and Cluster Dynamics

The simulations in the previous section also found that accreting clusters tend to shrink as mass is added onto the stars (Bonnell et.al. 2001a). In order to understand why this happens let us consider the energy of the stars in the cluster potential (c.f. Bonnell, Bate Zinnecker 1998):

$$E_{stars} = \frac{p^2}{2M_{stars}} - \frac{GM_{stars}M_{tot}}{R}, \quad (4)$$

where p is the total momentum of the stars, M_{stars} is the mass in stars, M_{tot} is the total mass in both stars and gas while R is the size of the system. In what follows we assume that the accreting gas has no net momentum and that therefore the stellar momenta is conserved during accretion. This assumption is justified as in general the accreting gas will be spherically infalling and, once the stars are virialised, there is no correlation between gas motions and stellar motions.

As mass is added while momentum is conserved, the kinetic energy of the stars decreases at the same time as the stars become more bound to the potential. The stars are then no longer in virial equilibrium with the potential and thus shrink until they revirialise at a smaller radius. The new radius reflects the new, lower energy as:

$$R_{cluster} = -\frac{GM_{tot}M_{stars}}{2E_{new}}. \quad (5)$$

As long as the accretion timescale is longer than the dynamical timescale, then the cluster can accrete and revirialise many times and thus shrink substantially. If, on the other hand, the accretion timescale is shorter than the dynamical timescale, then the cluster can only shrink by a factor of 2 after the accretion has finished. Under the condition of slow accretion, the rate of cluster shrinkage can be estimated by considering that accretion occurs at a constant radius and then shrinks to revirialise, reflecting the new energy. Thus

$$\left(\frac{\partial E}{\partial M_{stars}}\right)_R = \left(\frac{dE_{new}}{dM_{stars}}\right). \quad (6)$$

Solving the above equation yields (Bonnell et.al. 1998)

$$R \propto M_{stars}^{-\alpha}, \quad (7)$$

where the value of α depends on whether the total mass is conserved ($\alpha = 2$ or whether it is proportional to the mass in stars ($\alpha = 3$). The latter possibility reflects the case when accretion occurs onto the core of the cluster and gas continues to infall from outside the core. Thus, the increase in the stellar density can be very large, given by

$$n \propto M_{stars}^{3\alpha}, \quad (8)$$

such that for $\alpha = 3$ and an increase in the stellar mass by a factor of three results in an increase in the density as $3^9 \approx 2 \times 10^4$.

We therefore take as our model the core of a cluster similar to the ONC. This core, containing ≈ 100 initially low-mass stars within ≈ 0.1 pc. The stars in the core accrete until they have reached intermediate masses ($\approx 5M_{\odot}$) by which time they have attained a sufficiently high density that stellar collisions and mergers occur to form the massive stars. Figure 3 shows the evolution of such a system as the stars accrete at a constant accretion rate of $2 \times 10^{-6}M_{\odot} \text{ year}^{-1}$ (from Bonnell et.al. 1998). The half-mass radius of the system is plotted as a function of time as are the collisional timescale and the accretion timescale. Once the cluster core has shrunk sufficiently such that the collisional timescale is shorter than the accretion timescale, stellar mergers dominate the mass buildup process. Two collisional timescales are plotted reflecting collisional radii of 0.1 and 0.01 au. The transition from accretion to mergers occurs after a few crossing times, corresponding roughly to 4×10^5 years.

6. Stellar Collisions and Binaries

The actual cross sections for collisions depends on the dynamics and the presence of circumstellar material. One of the crucial factors is the formation of binaries as they then have a much larger cross section for further interactions. There are two ways in which binary systems can form. Firstly, they can form through tidal capture encounters. This is most important for near-equal mass encounters. Most encounters involving the more massive stars in the core are with lower-mass stars. These encounters do not generally result in tidal captures due to the disparate interior densities of the stars. Instead, the lower-mass star can be tidally disrupted to form a circumstellar disc. This results in the second binary formation mechanism as a subsequent encounter that passes through the disc gets captured due to the binding energy of the disc (Davies et.al., in preparation). Such binary systems will either merge on subsequent encounters or exchange in a higher-mass star to form a near equal-mass binary, that may itself merge in further encounters.

In either case, a high frequency of near-equal mass binary systems should result from a system where stellar collisions are occurring. This agrees with the finding that many O stars are members of short-period binary systems (Mason et.al. 1996). This is also the case in O-stars found in the centre of open clusters where they all appear to be in close binary systems with stars of comparable masses (Mermilliod 2001).

7. Accretion and Cluster Dynamics: the UKAFF simulation

In order to study the dynamics and evolution of an accreting cluster we have performed a numerical simulation of gas accretion in a cluster containing 1000 stars (Bonnell & Bate, in preparation). This simulation, performed on the UKAFF supercomputer with 10^6 SPH particles, follows the gas and stellar dynamics as the stars accrete. The primary aims of this simulation were to investigate whether an actual stellar and gas dynamical system would react according to our simple prescription and to see if the stellar interactions would destroy the cluster core before the necessary densities for collisions occurs. The maximum density in the cluster, as well as the density at the half-mass radius are plotted as a function of time in Figure 4. We see that the density increases dramatically after about one free-fall time. The mean density of the cluster increases by a factor of ≈ 20 while the peak density increases by over 10^4 up to 10^5 . This large increase in stellar density implies a large decrease in the timescale for collisions and mergers. If we take the cluster's initial conditions as being those present in the ONC, then we have an initial mean density of 10^3 stars pc^{-3} and a peak density of 2×10^4 stars pc^{-3} (McCaughrean & Stauffer 1994). In the UKAFF simulation the peak density increases by a factor of $> 10^5$ times the initial mean density. This then corresponds to stellar densities of $n \gtrsim 10^8$ stars pc^{-3} . This stellar density is sufficient to produce significant numbers of stellar collisions in the cluster core.

Accretion results in a centrally condensed cluster with a $n \propto r^{-2}$ stellar density profile. Figure 5 plots the distribution of stellar densities calculated as the volume necessary to contain 10 stars. The maximum density is considerably

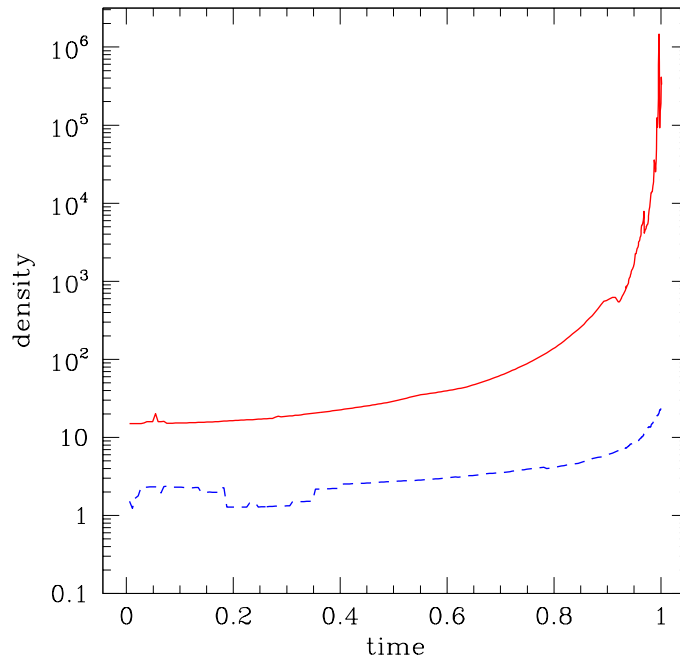


Figure 4. The evolution of the mean (dashed line) and maximum (solid line) stellar density is plotted as a function of time in units of the initial free-fall time. The maximum density increases dramatically near the end of the simulation, reaching values at which stellar collisions can occur in significant numbers. The maximum density is calculated by computing the volume needed to contain 10 stars while the mean density is averaged over stars near the half-mass radius.

higher than the mean density of $n \approx 20$, but is contained in a core which occupies only the innermost ≈ 0.01 of the half-mass radius.

In the UKAFF simulation, collisions are assumed to occur when two stars pass within 1 au of each other. This value is much larger than the stellar radii but comparable to the binary separations considered above. In any case, as shown in Bonnell et.al. (1998), the actual collisional radius affects only the delay until the cluster has shrunk sufficiently for collisions. Using the above collisional radius, 15 collisions occur during the UKAFF simulation. About half of these involve the more massive stars including a near equal-mass collision which results in the most massive star having a mass of ≈ 100 times the initial stellar masses. We thus can conclude that an accreting cluster can contract far enough such that significant stellar collisions occur which result in the formation of massive stars. The evolution of the mean and maximum masses during the simulation are plotted in Figure 6. We see that the maximum mass increases dramatically through both accretion (smooth increase) and collisions (jumps). As noted above, the maximum mass reaches a value ≈ 100 times the initial stellar mass. At the same time the mean stellar mass only increases by $\approx 70\%$ during

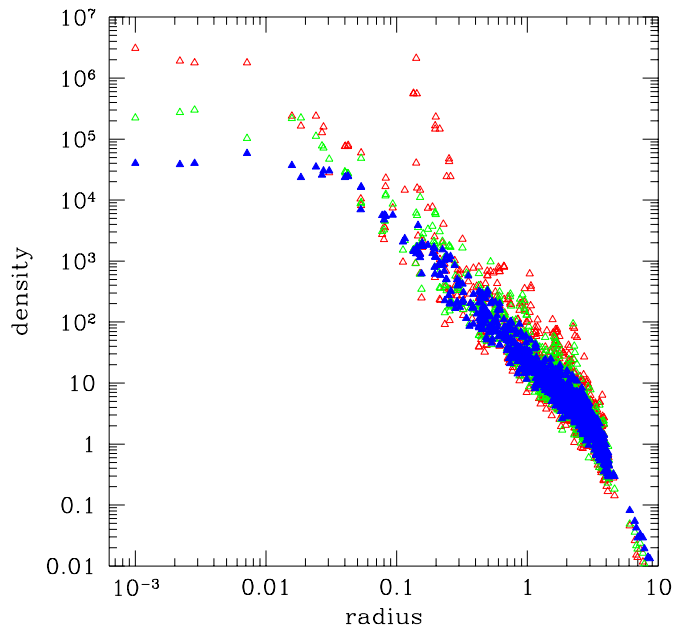


Figure 5. The distribution of stellar densities at the end of the UKAFF simulation is plotted as a function of radius in the cluster. The density is calculated by computing the volume needed to contain (from the top) 3, 5 (both open triangles) or 10 stars (filled triangles). The half-mass radius of the cluster is at $r \approx 1$.

the evolution. Many of the mergers involving the most massive star involve lower-mass impactors as is expected. Two mergers near the end of the simulation involve near-equal mass components and thus significantly contribute to the mass. The mean stellar mass in the cluster core is also plotted in Figure 6. This mean mass in the core increases dramatically but is only half due to the most massive star. Thus the cluster has been mass segregated due to the accretion and collisions.

It is also worth noting that the cluster stars tend to be in small groups, and along filaments (see figure 7 below). These configurations increase collisional rates and thus the ability for collisions to form massive stars. Furthermore, if the absence of collisions, the maximum stellar densities would have been considerably higher.

8. Collimating Outflows

Massive stars are generally associated with energetic outflows. These outflows are often seen as evidence for a circumstellar disc which would most likely be destroyed in regions sufficiently dense to allow for stellar mergers. The implication of a stellar disc for these outflows is not at all certain as the outflows are

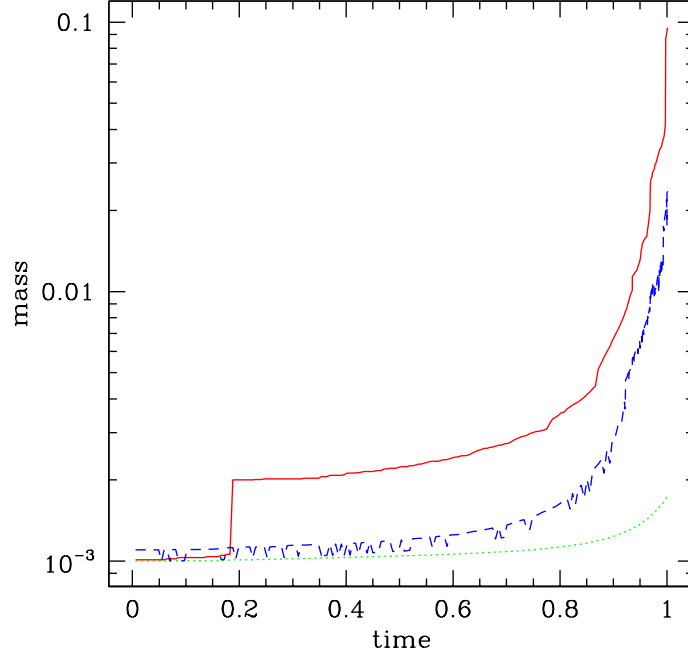


Figure 6. The evolution of the mean (dotted line) and maximum (solid line) stellar mass is plotted as a function of time in units of the initial free-fall time. The mean stellar mass inside the cluster core is also plotted (dashed line). The maximum mass increases in jumps every time there is a merger and smoothly due to accretion. Note that there are two major mergers near the end of the simulation which contribute significantly to the maximum mass. The maximum mass increases by a factor of 100 while the mean stellar mass has increased by only 70 %. The mean stellar mass in the core also increases dramatically signifying a mass segregated cluster.

generally poorly collimated and thus of a fundamentally different type than the well-collimated outflows from low-mass stars.

An alternative to disc collimation is that there is present some structure in the accretion flow or general circumstellar environment which tends to collimate (poorly) any outflow from the massive stars. Figure 7 shows the configuration of the stars and the gas towards the end of the UKAFF run. The gas (and stars) are far from uniformly distributed. Instead, the gas displays filamentary shapes pointing towards the cluster centre. The stars are generally situated along the filaments and tend to be in small groups. Both the gas and the stars move along these filaments which increases the rate of collisions.

The filamentary structures present in the accretion flows in the cluster centre are due to gravitational instabilities. The gas initially contains some 1000 Jeans mass, in agreement with its previous fragmentation to form the 1000 stars. In such a system, gravity tends to increase any over densities and to reduce the

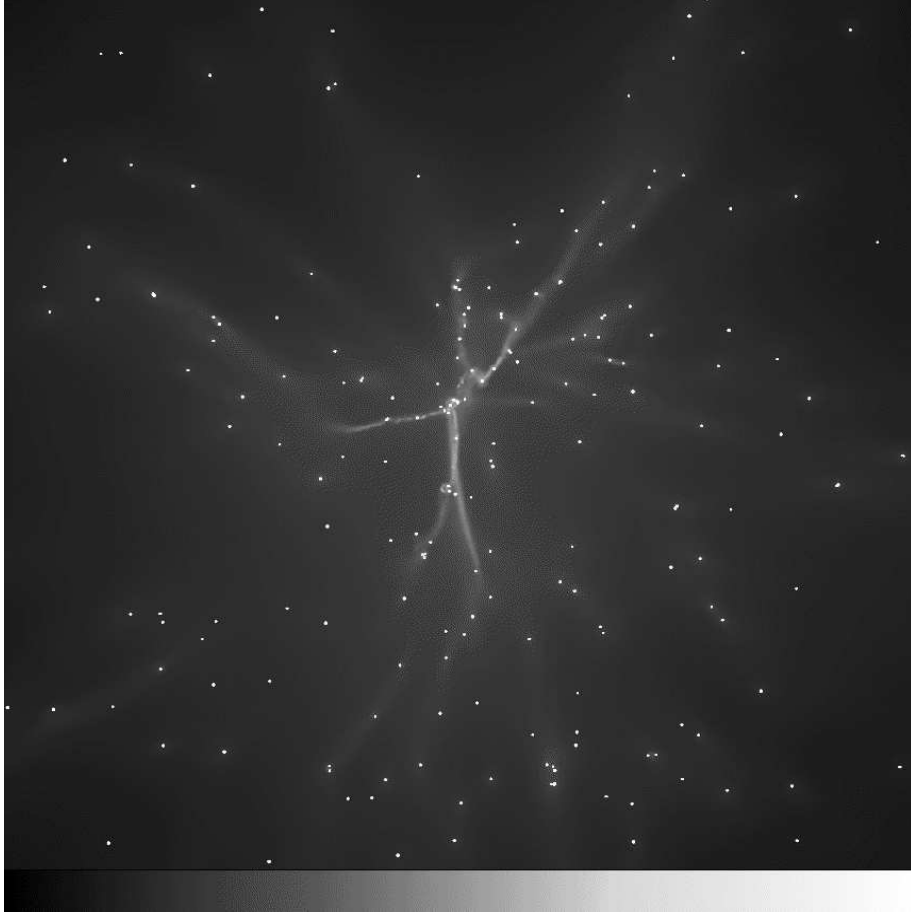


Figure 7. The distribution of gas and stars are shown near the end of the UKAFF simulation. The region plotted is the central core of radius one half the half-mass radius. The gas forms into filaments which may help collimate any outflows.

dimensions of the structure. In this way, the over densities can grow and form into filamentary structures. Such structures are a possible source for the collimation of the massive stars' outflows. Further numerical simulations will have to be performed in order to test this speculation. It should be noted, however, that any collimation that does result from this structure is likely to be fairly open and as such this mechanism is not likely to result in the formation of jet-like outflows. Any such highly collimated outflows around young O stars would thus be difficult to explain with this stellar merger mechanism.

9. Implications of collisions

There are many implications of this collisional formation mechanism for massive stars which need to be considered. The most significant of these is the effect

of the energy involved in the collisions. As two $10M_{\odot}$ stars collide, the energy involved is of order 10^{49} ergs. This much energy will puff up the stars which will contract on their Kelvin-Helmholtz timescale. The increased size of the star will make it more susceptible to further collisions. if we assume that the energy is radiated over some 10^4 years, then the energy flux will be $\approx 10^{38}$ ergs s^{-1} . Indeed, a fraction of the kinetic energy may be released on much shorter timescales and result in an x-ray flare. Such an event should be observable (see chapters by H. Zinnecker and J. Bally). It is alkso probable that the energy released in this way would contribute to the re-expansion of the cluster core.

10. Summary

The formation of massive stars is a complicated process in which the environment is likely to play a crucial role. Massive stars form in the cores of stellar clusters where the expected fragment mass is low. Accretion in clusters forms higher-mass stars from low mass stars and naturally results in a mass segregated cluster as the higher accretion rates in the core result in more massive stars there. This process also results in a two-slope IMF similar to that observed in stellar clusters and in the field.

The accretion onto the stars in the cluster forces it to shrink and revirialise at a smaller radius. if the accretion is slower or comparable to the local dynamical time (say of the cluster core), then accretion can force the core to continue shrinking until it has reached sufficient densities where stellar collisions occur. These collisions can then result in the formation of massive stars. A recent simulation using the UKAFF supercomputer has shown that an accreting cluster can indeed attain the required stellar densities and that mergers can play an important role in the formation of massive stars. The accretion flow is susceptible to the formation of filamentary structure which may play a crucial role in collimating any outflow from massive stars. It would be unlikely to be able to collimate a jet-like outflow.

11. Acknowledgments

The results presented here are partially based on numerical simulations performed with the United Kigndom's Astrophysical Fluid Facility (UKAFF) supercomputer.

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